Hard Burst Emission from the Soft Gamma Repeater SGR 1900+14

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ABSTRACT

We present evidence for burst emission from SGR 1900+14 with a power-law high energy spectrum extending beyond 500 keV. Unlike previous detections of high energy photons during bursts from SGRs, these emissions are not associated with high-luminosity burst intervals. Not only is the emission hard, but the spectra are better fit by Band's GRB function rather than by the traditional optically-thin thermal bremsstrahlung model. We find that the spectral evolution within these hard events obeys a hardness/intensity *anti*-correlation. Temporally, these events are distinct from typical SGR burst emissions in that they are longer (~ 1 s) and have relatively smooth profiles. Despite a difference in peak luminosity of $\gtrsim 10^{11}$ between these bursts from SGR 1900+14 and cosmological GRBs, there are striking temporal and spectral similarities between the two kinds of bursts, aside from spectral evolution. We outline an interpretation of these events in the context of the magnetar model.

Subject headings: stars: individual (SGR 1900+14) — stars: pulsars — X-rays: bursts

1. Introduction

Soft gamma repeaters (SGRs) constitute a group of high-energy transients named for the observed characteristics which set them apart from classical Gamma-Ray Bursts (GRBs). SGRs emit brief (~ 0.1 sec), intense (up to $10^3 - 10^4$ $L_{\rm Edd}$) bursts of low-energy γ-rays with recurrence times which range from seconds to years (Kouveliotou 1995). The vast majority of SGR burst

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spectra ($\gtrsim$ 20 keV) can be fit by an Optically-Thin Thermal Bremsstrahlung (OTTB) model with temperatures between 20 and 35 keV (Fenimore, Laros, & Ulmer 1994; Göğüş et al. 1999). These spectra show little or no variation over a wide range of time scales (Fenimore et al. 1994), both within individual bursts, and between source active periods which cover years. There have been some exceptions, however, where modest hard-to-soft evolution within bursts from SGR 1806−20 was detected (Strohmayer & Ibrahim 1997).

During the past 20 years, two giant flares have been recorded from two of the four known SGRs: one from SGR 0526 − 66 on 5 March 1979 (Mazets et al. 1979), and one from SGR 1900+14 on 27 August 1998 (Hurley et al. 1999a). These flares differ from the more common bursts in many ways. They are far more energetic (by 3 orders of magnitude in peak luminosity), persist for hundreds of seconds during which their emission is modulated at a period that reflects the spin of an underlying neutron star, and have harder initial spectra. The hard spectra of the peak of these flares have OTTB temperatures 200 − 500 keV (Fenimore et al. 1991; Hurley et al. 1999a; Mazets et al. 1999a), although this model should not necessarily be taken as an accurate valid description of these spectra as severe dead-time problems for most instruments limited the efficacy of spectral deconvolution. Feroci et al. (1999) require the first $\sim$ 67 s of the August 27$^{\rm th}$ flare be fit with a two-component spectrum, consisting of an OTTB (31 keV) and a power-law (− 1.47 photon index). Hard burst emission has also been detected during the brightest burst recorded from the newly discovered SGR 1627−41 (Woods et al. 1999a; Mazets et al. 1999b). Further evidence for hard emission from SGRs comes from RXTE observations of SGR 1806−20. For a small fraction of the more common short events, high OTTB spectral temperatures in the range 50 − 170 keV were measured (Strohmayer & Ibrahim 1997).

Here, we present strong evidence for spectrally hard burst emission from SGR 1900+14 during its recent active episode which started in May 1998. Two events recorded with BATSE which are positionally consistent with SGR 1900+14 and temporally coincident with the recent active period of the source, show temporal and spectral signatures quite distinct from typical SGR burst emissions. We show that although the time-integrated spectrum of each event resembles a classical GRB spectrum, spectral evolution is found which obeys a hardness/intensity anti-correlation, never before seen in GRBs.

2. Burst Association with SGR 1900+14

On 22 October 1998, during a period of intense burst activity of SGR 1900+14 (Woods et al. 1999b), BATSE triggered at 15:40:47.4 UT on a $\sim$ 1 s burst with a smooth, FRED-like (Fast Rise Exponential Decay) temporal profile which is commonly seen in GRB light curves, but is rare for SGR events. This burst was located near SGR 1900+14 (Figure 1), but was longer than

typical bursts from this source and its spectrum was much harder[8] (Figure 2a). Using Ulysses and BATSE, an IPN annulus was constructed and the joint BATSE/IPN error box (Figure 1) contained the known source location of SGR 1900+14 (Frail, Kulkarni & Bloom 1999).

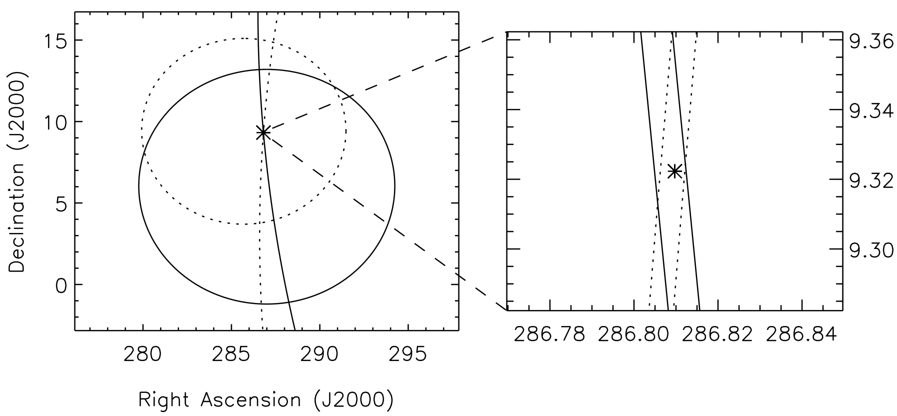

Fig. 1.— Localizations of 981022 (dotted) and 990110 (solid) with BATSE (circles denote 90% statistical + systematic error radii) and BATSE/Ulysses IPN arcs (99% statistical + systematic error). VLA location of SGR 1900+14 is denoted by the asterisk.

Without invoking any assumptions about source activity, we estimate the probability that a GRB within the BATSE database with an IPN arc would contain any known SGR by chance. For our purposes, we will assume GRBs are isotropic and the angular size of the known SGR error boxes are small compared to the joint BATSE/IPN error box. The probability p reduces to $p \approx\ (1/4\pi)\ NA$ where N is the number of known SGRs and A is the area of the burst error box in steradians. With four known SGRs, we find a chance probability of 3×10^{-6} that a GRB with the given error box area will overlap a known SGR. We now normalize this probability by multiplying by the number of trials (i.e. the number of BATSE/Ulysses IPN arcs as of March 1999, which is 641), which gives the probability of a chance association of 2×10^{-3}. The burst was detected during a period when SGR 1900+14 was burst active (a fact not used in the probability calculation), further strengthening the association.

[8]The similarities of this event with GRBs in spectrum and temporal structure was noted independently by D. Fargion (1999)

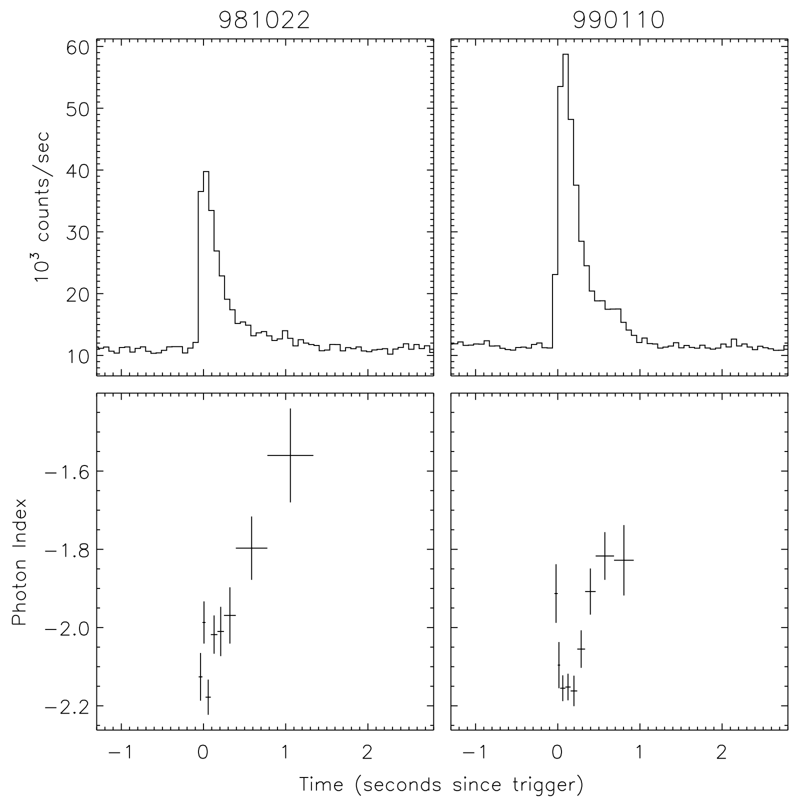

Fig. 2.— light curves (25 − 2000 keV) of two bursts from SGR 1900+14 detected with BATSE. BATSE trigger 7171 (981022) is shown in panel (a) and trigger 7315 in panel (b). Panels (c) and (d) give the photon index as a function of time to illustrate the spectral evolution observed during these events.

Ten weeks later on 10 January 1999 at 08:39:01.4 UT, a strikingly similar burst (Figure 2b) was recorded with BATSE, which again located near SGR 1900+14. This burst also triggered Ulysses, so an IPN annulus was constructed which again contained the position of SGR 1900+14 (Figure 1). Using the same arguments as before, we find an upper limit to the probability that the burst and any known SGR are related by chance coincidence of 3×10^{-3}. The combined probability (product of the two individual probabilities) that these two events are GRBs with BATSE/IPN error boxes that are consistent with a known SGR by chance coincidence is 6×10^{-6}.

An alternative possibility is that these two bursts constitute two gravitationally lensed images of the same GRB (Paczyński 1986). However, we consider this highly unlikely given the positional coincidence of SGR 1900+14, the temporal correlation with a known burst active period for the source, and the anti-correlation between hardness and intensity (see section 3). We conclude that these two bursts originated from SGR 1900+14.

3. Burst Spectra

To fit the time-integrated spectrum for each burst, we used High Energy Resolution Burst (HERB) data which have 128 energy channels covering 20 – 2000 keV (see Fishman et al. 1989 for a description of BATSE data types). We fit a third-order polynomial to approximately 300 sec of pre-burst and post-burst data and interpolated between these intervals to estimate the background at the time of the burst. This background was subtracted and we fit the resulting burst spectrum using WINGSPAN (WINdow Gamma SPectral ANalysis) to three models: an OTTB (dN/dE $\propto$ E^{-1} exp[-E/kT]), a simple power-law, and Band's GRB function (Band et al. 1993). We find that for each burst, the spectrum is not well characterized by the OTTB model based upon the large value of χ^2_ν (Table 1). Using a $\Delta\chi^2$ test between the Band and OTTB models, we find the Band function is strongly favored over the OTTB, with probabilities of 4.6 $\times$ 10^{-7} and 7.2 $\times$ 10^{-11} that these χ^2 differences would occur by chance for the respective bursts. Furthermore, the Band function is favored over the simple power-law for the second, brighter event with a significance level of 1.3 $\times$ 10^{-3}, although inclusion of a low-energy cutoff with the power-law model eliminates this advantage. Figure 3 shows the data and folded Band model for each burst.

For comparison to past results, we have included the OTTB fit parameters (Table 1) to clearly demonstrate the difference between the spectra of these bursts and typical SGR burst emissions. Specifically, for SGR 1900+14 during its recent active episode, a weighted mean of 25.7 $\pm$ 0.8 keV was found for the OTTB temperature of 22 events detected with BATSE (Göğüş et al. 1999). Clearly, the temperatures found for these two bursts are much higher than these typical values.

Using data with coarser spectral resolution, but finer time resolution, we fit multiple segments of each burst in order to search for spectral evolution. For the initial rise of each event, we used Time-Tagged Event (TTE) data which have only 4 energy channels but 2 μs time resolution. For the peak and tail, we used Medium-Energy Resolution (MER) data which have 16 energy channels and 16 ms time resolution. In order to sustain good signal-to-noise for a reasonable parameter determination, the bursts were divided into 8 and 9 intervals, respectively. Guided by our fit results of the time-integrated spectra and our limited number of energy channels, we chose to fit the power-law model to these spectra. We find significant spectral evolution through each burst as the power-law photon index varies between – 1.5 and – 2.4 (Figures 2c and 2d). We note a general soft-to-hard trend in the time evolution of the spectra of these bursts. This appears to be a consequence of a relatively faster temporal rise than decay and an intensity/hardness anti-correlation for these events (Figure 4). To quantify the significance of this correlation, we calculated the Spearman rank-order correlation coefficient ($\rho = -0.86$) between the energy flux and photon index. The probability of obtaining a coefficient of this value from a random data set is 8.3 $\times$ 10^{-6}, thus the anti-correlation is significant.

The peak fluxes and fluences of the two events are not exceptional when compared to other burst emissions from this source. We find peak fluxes (0.064 s timescale) of (2.94 $\pm$ 0.15) and

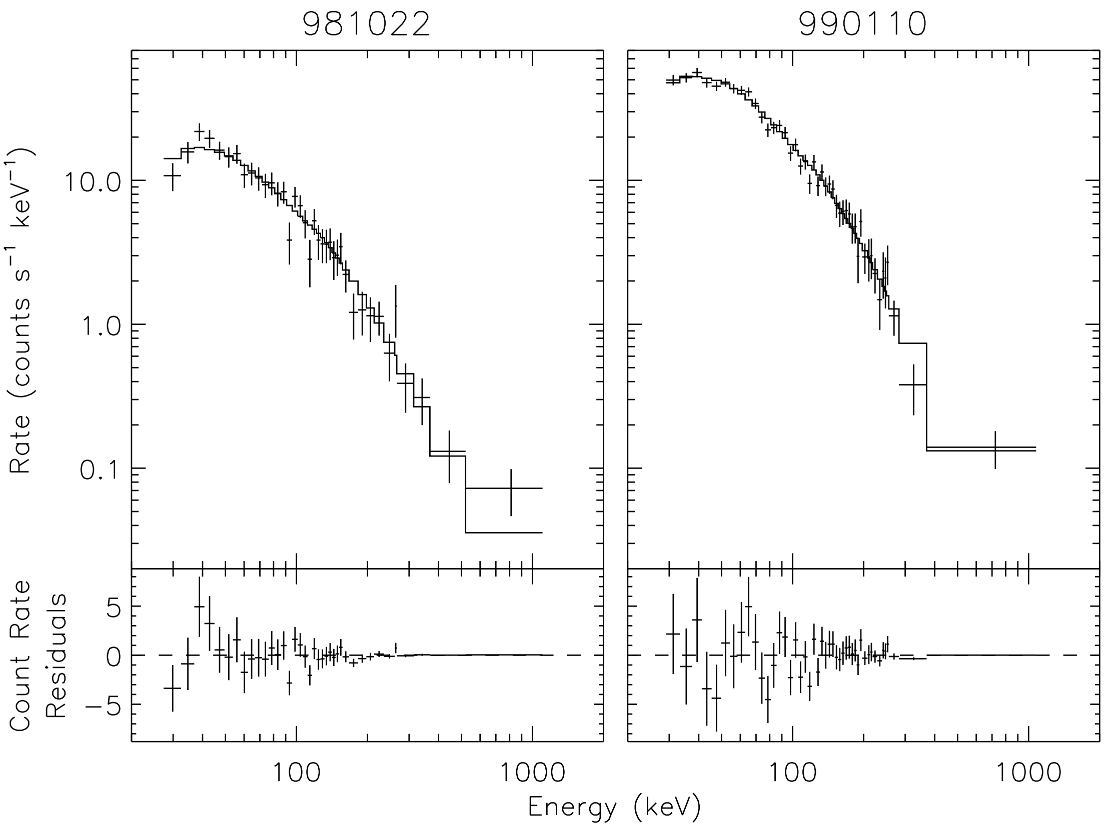

Fig. 3.— Count spectrum of 981022 (a) and 990110 (b) as fit to Band's GRB function. See Table 1 for spectral fit information. The spectrum has been binned for display purposes.

$(4.96 \pm 0.18) \times 10^{-6}$ ergs cm^{-2} s^{-1} and fluences (25 – 2000 keV) of (1.14 ± 0.04) and (1.85 ± 0.04) $\times\ 10^{-6}$ ergs cm^{-2} for the bursts of 981022 and 990110, respectively. For a distance of 7 kpc (Vasisht et al. 1994), these correspond to peak luminosities 1.7 and 2.9×10^{40} ergs s^{-1} and burst energies 0.65 and 1.1×10^{40} ergs (assuming isotropic emission). The ranges of peak fluxes and fluences for SGR 1900+14 bursts observed recently with BATSE are $0.3 - 20 \times 10^{-6}$ ergs cm^{-2} s^{-1}, and $0.02 - 25 \times 10^{-6}$ ergs cm^{-2}, respectively (Göğüş et al. 1999). The measured values for these bursts with harder spectra are well within the corresponding observed ranges.

4. A Comparison with Observed GRB Characteristics

For each event, we have calculated two quantities that are traditionally used to delineate between the two classes (Kouveliotou et al. 1993) of GRBs in the BATSE catalog, specifically t_{90} and spectral hardness (Ch 3/Ch 2). We find t_{90} durations of 1.2 ± 0.2 and 0.9 ± 0.2 s, and fluence

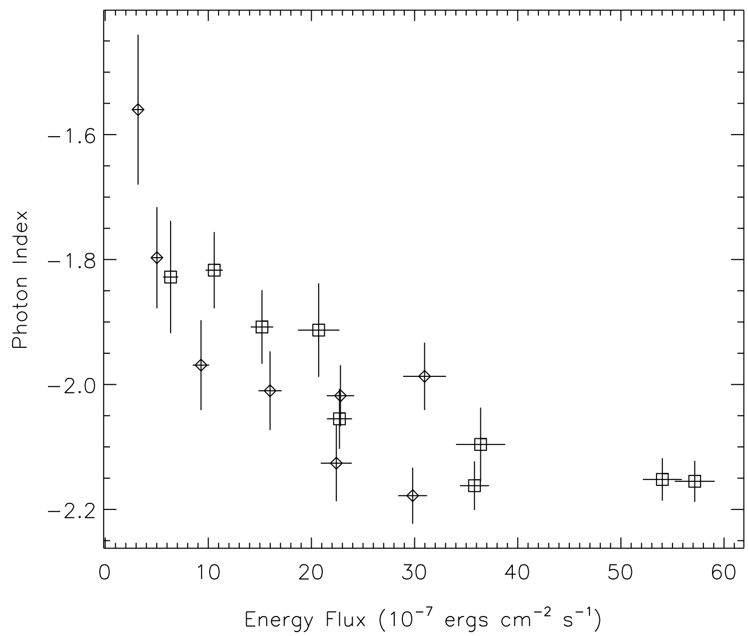

Fig. 4.— Energy flux vs. photon index for 981022 (diamonds) and 990110 (squares).

hardness ratios (3/2) of 1.9 ± 0.1 and 2.1 ± 0.1 for the bursts of 981022 and 990110, respectively. When plotted together with the reported values of the 4Br catalog (Paciesas et al. 1999), we find these two bursts fall outside the main concentrations of each distribution (i.e. the long, soft class and the short, hard class), but nearer the centroid of the short, hard class. We are currently looking more closely at events in the same region of this diagram that were classified as GRBs.

Given the spectral similarities between these two events and a fair fraction of GRBs, the time-integrated spectrum is not sufficient to distinguish these bursts from GRBs. Many GRBs show a strong hardness/intensity correlation within individual bursts (Ford et al. 1995; Preece et al. 1999), but to the best of our knowledge, a consistent *anti*-correlation throughout a GRB has never been seen. The two bursts from SGR 1900+14 do, however, show a strong hardness/intensity anti-correlation (Figure 4). If this behavior is inherent to all *hard* SGR events, it would be a useful diagnostic (but secondary to location) with which to select them.

5. Discussion

We have shown strong evidence for hard emission from SGR 1900+14 during two bursts of average intensity as observed with BATSE. It is clear that this type of burst emission in SGR 1900+14 is rare (1% of the SGR 1900+14 events acquired with BATSE during the 1998-1999

active period). Their occurrence following the August 27 flare may suggest a causal relationship, but this is difficult to pin down given the rarity of hard events and the global enhanced burst activity at the time. The clear distinction between these two events in hardness, spectral form, spectral evolution, duration, and lack of temporal variability suggests these bursts are created either by physical processes different from those which produce the more common, soft events, or in a region whose ambient properties that effect the emitted radiation (e.g. magnetic field, optical depth, etc.) are different.

The proposed identification of SGRs with very strongly magnetized neutron stars (Duncan & Thompson 1992) has received strong support from the discovery that both SGR 1806−20 and SGR 1900+14 are X-ray pulsars spinning down at rapid rates (Kouveliotou et al. 1998, 1999; Hurley et al. 1999b). In this magnetar model, the typically soft SGR bursts are explained in the following way. The internal magnetic field is strong enough to diffuse rapidly through the core, thereby stressing the crust (Thompson & Duncan 1996). A sudden fracture injects a pulse of Alfvén radiation directly into the magnetosphere, which cascades to high wavenumber and creates a trapped fireball (Thompson & Duncan 1995; Thompson & Blaes 1998). The soft spectrum arises from a combination of photon splitting and Compton scattering in the cool, matter-loaded envelope of the fireball.

The relative hardness of the two reported events, combined with luminosities in excess of 10^{40} erg s^{-1}, points directly to an emission region of shallower scattering depth, $\tau_{\rm es} < 1$, situated outside $\sim 10^3(L_X/10^{40}$ erg s$^{-1})$ neutron star radii. Inverse Compton emission is suggested by the lack of a correspondence between the spectral break energy and a cooling energy at this large a radius. For example, bulk Alfvén motions are an effective source of Compton heating even in the absence of Coulomb coupling between electrons and ions (Thompson 1994). In certain circumstances, one expects that Alfvén radiation will disperse rapidly throughout the magnetosphere: if the initial impulse occurs on extended dipole field lines; or if it involves a buried fracture of the crust. This rapid dispersal is made possible by the strong coupling between external Alfvén modes and internal seismic waves (cf. Blaes et al. 1989). The wave energy is then distributed logarithmically with radius, with the wave amplitude $\delta B/B$ approaching unity at the Alfvén radius $R_A/R_\star \simeq 900\,(B_\star/4.4\times10^{14}\ {\rm G})^{1/2}\,(L_A/10^{40}\ {\rm erg\ s^{-1}})^{-1/4}$ (Thompson & Blaes 1998). Here $B_\star$ is the polar dipole magnetic field, L_A is the luminosity in escaping waves, and $R_\star \simeq 10$ km. Damping by leakage onto open field lines (which extend beyond the Alfvén radius) occurs on a timescale $t_{\rm damp} = 3(2R_A/R_\star)(R_\star/c) = 0.2\,(B_\star/4.4\times10^{14}\ {\rm G})^{1/2}\,(L_A/10^{40}\ {\rm erg\ s^{-1}})^{-1/4}$ s. This lies close to the FWHM of the two reported bursts. Wave excitations near the neutron star undergo a turbulent cascade on a similar timescale, and will generate softer seed X-ray photons (Thompson et al. 1999).

Independent of the detailed physical mechanism, these observations demonstrate that a Galactic source – probably a strongly magnetized neutron star with a large velocity – is capable of producing a burst of γ-rays whose time-integrated spectrum resembles that of a classical GRB. The similarity is remarkable in light of the difference in peak luminosities of $\gtrsim 10^{11}$ (modulo

beaming factors). However, the two bursts from SGR 1900+14 presented here are by no means 'typical' GRBs, given their low E_{peak} values, unusual spectral evolution, and their position in the duration-hardness plane. Furthermore, we know the currently active SGRs in our Galaxy lie close to the Galactic plane ($z_{rms} \simeq 66$ pc), so their contribution to the BATSE GRB catalog must be minimal on account of the isotropic spatial distribution of GRBs. A larger contribution from older magnetars that have moved away from the Galactic plane is conceivable, but it would require that the preponderance of hard bursts to soft bursts increases tremendously with age.

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Table 1. Spectral fit summary

Burst	Model	χ^2/dof	kT or E_{peak} (keV)	Photon index[a]
981022	OTTB	119.4/96	102 ± 5	–
	Power law	92.7/96	–	– 1.91 ± 0.06
	Band's GRB	90.2/94	54 ± 50	– 1.96 ± 0.08
990110	OTTB	139.8/95	94 ± 4	–
	Power law	106.4/95	–	– 2.06 ± 0.03
	Band's GRB	93.1/93	59 ± 11	– 2.19 ± 0.06

[a]For Band's GRB function, the high energy index β is given here. The low energy index α is not well determined due to the low E_{peak} values.